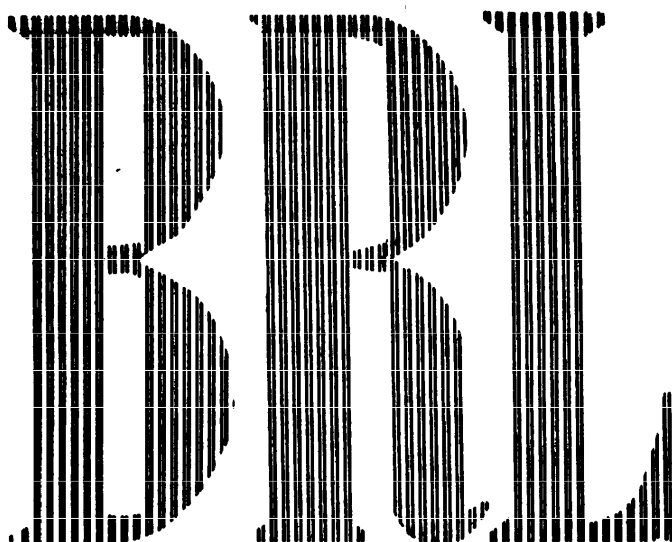


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REPORT NO. 1095
January 1960

MINIATURE HOT WIRE PRESSURE GAGES FOR
WIND TUNNEL WORK

Herbert J. Bomelburg

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January 1960

MINIATURE HOT WIRE PRESSURE GAGES FOR WIND TUNNEL WORK

ABSTRACT

A Pirani type hot wire pressure gage has been made so small that it has been possible to install it within the usual pressure holes of wind tunnel models. Its expected temperature drift has been compensated and static and pitot pressures have been measured. As the response time of such a small gage is very short, it can also be used for indicating unsteady and turbulent flow conditions. Two symmetrical gages of this kind have been used as a sensitive flow angle meter.

INTRODUCTION

Quite a variety of methods, based on several different principles, have been applied in measuring pressures in wind tunnel tests. The most common ones are methods which use long pressure leads from the pressure holes inside the tunnel or model to manometers or other gages outside the tunnel. This represents the most straightforward method, which is simple and reliable and therefore has a great appeal to test engineers.

There are certain disadvantages, however, in these methods. For example, it takes a rather long time to reach pressure equilibrium with the long and narrow pressure leads, especially in supersonic wind tunnels which normally run at low test section pressures. Another disadvantage is the rather large cross section of a single pressure lead, which can hardly be made smaller than 1 mm^2 for practical reasons. Therefore, many attempts have been made to build pressure gages so small that they can be installed within the wind tunnel models, with only thin electrical leads connecting the model with the outside instrumentation. These trends have been rather successful with large tunnels where large models can be accommodated. There are limitations, however, because of the size of the pressure transducers, which are still in the order of 1 cm diameter for the smallest type. The trend for further miniaturization of such pressure gages is therefore quite justified.

This paper describes a pressure transducer which is essentially a very small version of the well known Pirani hot wire gage. These new gages can be made at least ten times smaller than the smallest conventional types.

PRINCIPLE OF OPERATION

The Pirani gage works on the principle that the heat loss from a thin heated wire to the surrounding gas becomes dependent on the pressure at low gas densities. The author has shown in another investigation* that the heat loss at constant temperature is a universal function of the Knudsen number, which is the ratio of the hot wire diameter to the mean free path in the gas.

*"The Heat Loss from Very Thin Heated Wires in Rarefied Gases". The Phys. of Fluids 2 pp. 717-718 (1959).

This means that a Pirani type pressure gage* can be used up to any pressure if only one can make the wire diameter small enough. For example, with a .5 micron wire, pressures around one atmosphere can be measured quite accurately. This seems to be the practical limit, however, as it is extremely difficult to handle wires of such small size.

DESCRIPTION OF THE GAGE

In this particular case, a hot wire (1.25 μ diam., Pt + 10% Rh) was mounted** across a ceramic tube of 1/16" OD as shown in Fig. 1. As the length-to-diameter ratio is in the order of 500, end effects are small and can be neglected. The connections to the wire and along the ceramic tube are made by silver conducting paint (firing type) so that this hot wire arrangement could be used to temperatures up to 1400°F.. The ceramic tube was sealed at the back and mounted in insulating holders.

The first experiment was performed with the hot wire in a pitot tube arrangement as shown in Fig. 2. One side of the hot wire was grounded to the tunnel and the other side was connected to an insulated copper wire leading out of the tunnel. The pitot tube could be closed at the front end and two holes on the sidewalls could be opened, so that the same arrangement could also be used as a static pressure probe.

Electrically the hot wire (HW) was connected to a Wheatstone bridge ABCD as shown in Fig. 3 and was operated at constant temperature. The potentiometer P between points C and D was set about 10% above the cold resistance (at room temperature) of the hot wire, which was around 130 ohms. This means that the bridge is in balance if the hot wire is about 30°C above its ambient temperature. This temperature is controlled by regulating the current with the two ten-turn potentiometers (R, 500 ohms and 100 ohms in series). The null indicator (M) is connected between points B and D. As the heat loss from the hot wire decreases with decreasing pressure, the resistance of R has to be increased in order to keep the bridge balanced.

* So far Pirani gages have been used nearly exclusively for vacuum work.

** Details of mounting such thin hot wires will be published separately in "The Review of Scientific Instruments" under the title: "Handling of Very Thin Wollaston Wires".

EXPERIMENTAL RESULTS WITH PITOT AND STATIC PRESSURE GAGES

In the first actual experiment with a hot wire mounted in a pitot tube in a $M = 4.63$ flow, the resistance R had to be increased to keep the bridge balanced, e.g. from 44.8 ohms at atmospheric pressure to 65.5 ohms at a pitot pressure of 75 mm Hg.

It was observed, however, that the reading drifted with time and that the resistance R had to be decreased slowly (to about 61.2 ohms) in order to keep the bridge in balance. The reason for this annoying feature is that the whole pitot tube assembly, which is originally at room temperature, slowly cools down in the cold supersonic flow. Therefore in order to keep the hot wire at its constant working temperature, the electric current flowing through it has to be increased accordingly.

In the next experiment the hot wire was used in a static pressure probe. As the static pressures in the same flow are much lower (in the order of 3 mm Hg) the resistance R had to be changed, e.g. from 45.2 ohms at atmospheric conditions to about 280 ohms. As the hot wire is so much more sensitive in this pressure range, a small variation of pressure will produce a sizable change of R . It was found that static pressures in this region could be read with an accuracy of about 1%. The static pressures in the test section were changed by varying the total head pressures in the wind tunnel supplying section. As these two pressures have to be proportional to each other for the same Mach number, it was rather easy to check the sensitivity of the hot wire pressure gage.

However, from experiments in still air at low pressures, it was found that the sensitivity of a hot wire pressure assembly can be increased at least by one order of magnitude if precision parts and instruments are used under optimum conditions. With the static pressure probe again, a marked drift occurred because of the cooling off of the whole assembly. It took about 1/2 hour before an equilibrium condition (within the accuracy of 1%) had been reached. This temperature drifting is certainly such a severe drawback of the HW pressure gage in this simple form that it prohibits its practical use in

wind tunnel work. However, in another application this drawback was found to be of less importance. As the response time of the gage is very short (probably less than a millisecond) it can be used for measuring turbulent and other pressure fluctuations*, because here the relative change of the pressure is more important than its actual absolute value.

Oscillograms of such turbulent pressure fluctuation have been taken with the use of an ordinary AC coupled low noise preamplifier (not compensated; hooked up to points B and C in Fig. 3). They look very similar to those taken with bare hot wires exposed directly to the flow. Approximately the same results were obtained whether the wires were assembled in pitot or in static pressure probes. The highest frequencies observed in the turbulent spectrum were in the order of 10 kc. It is, of course, still completely unknown how such a gage would respond quantitatively to the different frequencies of the turbulent spectrum, as the thin airduct in front of the hot wire introduces some kind of damping. On the other hand the lowest self-resonant frequency of the air column inside the gage seems to be in the order of 100 kc. Probably much work has to be done before one can draw really quantitative conclusions with respect to fast pressure fluctuations from such encapsuled hot wires.

There are some cases, however, where such crude HW pressure gages might be of immediate help. Thus it was observed that during the starting and the shutdown process of the wind tunnel the turbulent pressure fluctuations were much higher (at least by a factor of 100) than those in the established flow. Also found was a noticeable increase of turbulence behind a shock wave. Furthermore, an unsteady flow was easily detectable by sudden pressure jumps which appeared to be 100 to 1000 times above the turbulent level. The same result showed up if the pressure hole was located in a region of separated flow. A normal uncapsuled hot wire of the same diameter (1.25 μ) would almost certainly break in such violent fluctuations. Oscillations of this

* L. J. F. Broer ; R. E. de Haan "Total Head Measurements in Fluctuating Flows." ZAMP (Festschrift Jakob Ackeret) Vol. IXb pp. 162-172 (1958).

kind were detectable even on the null indicator of the Wheatstone balance in the form of a jerking needle. Thus a hot wire within a pressure hole beneath the surface of a wind tunnel model is able to indicate the status of the boundary layer at least qualitatively. Such gages could even be built into rotating models, as low noise commutators are available today.

EXPERIMENTAL RESULTS WITH HOT WIRE PRESSURE GAGES FOR DETERMINING FLOW INCLINATIONS

If a second resistor in the Wheatstone bridge would have the same temperature dependence and would also be exposed to the same environmental temperature as the HW itself then it would be possible to compensate the temperature drift completely. This can actually be accomplished in several ways without great technical difficulties, as will be shown later in experiments with a wedge carrying two symmetrical hot wires. But first it shall be shown how such a wedge can be used primarily for precision measurements of flow inclinations. As shown in Fig. 4, two hot wires ($2.5\mu\phi$)* were mounted symmetrically in a wedge. One side of each hot wire was electrically grounded; the other sides were brought out in two electrical leads and were connected to the Wheatstone bridge as shown in Fig. 5.

In the actual experiment it turned out that at room temperature, hot wire 1 (HW_1) had a resistance of 35 ohms (exactly 34.54 ohms) and hot wire 2 (HW_2) a resistance of 30 ohms (exactly 29.86 ohms). It was again assumed that the hot wires should operate at 10% above their cold resistance, which means at 38.00 ohms and 32.84 ohms respectively. Therefore the potentiometer R_1 was set at 38.00 ohms and R_2 at 32.84 ohms, so that the bridge would be in balance if the two hot wires assume the same working temperature. In fact the bridge would exactly be in balance at any temperature if the

*The two hot wires should have identical characteristics. However, practically they always will differ a little bit in their effective length, i.e., their electrical resistance. But this is not very important.

conditions at the wire and the hot wires themselves were truly identical*. But then there would not be any indication whether the proper working temperature had been reached and in such a case it would be very easy to destroy the hot wires by too great a current. For safety reasons, therefore, an additional potentiometer R_a was hooked up to the bridge. R_a could be inserted into the circuit in place of HW_2 by the switch S_2 . R_a was set at exactly the same value as R_2 .

When the flow in the tunnel had been established, the current was switched on by S_1 with the full resistance of the ten-turn potentiometer R in line. The switch S_2 was connected to R_a . Usually the null indicator M will then show a small current which will first increase slowly when R is decreased, come to a maximum, and then sharply go to zero. This means at this point the correct working temperature of HW_1 has been reached. Now HW_2 is connected into the circuit by switching S_2 . If the flow conditions are truly identical on both sides of the wedge (zero angle of attack) then the null indicator should stay at zero. In the wind tunnel ($M = 4.0$) experiment, the angle of attack could be changed from the outside, and the null indicator could therefore easily be brought to zero by adjusting the angle of attack within a fraction of a degree. In this way flow inclinations can be measured very fast and accurately. There are several ways to calibrate the electrical non-linear output signals of the bridge against angular inclination. One way is to measure the voltage on the null indicator with a more sensitive instrument (microvoltmeter). From these tests it was estimated that it is possible to reach an accuracy of about $.01^\circ$ in determining the flow angle by this method.

* If R_{W1} and R_{W2} are the cold resistances and T_{W1} and T_{W2} the working temperatures of the hot wires HW_1 and HW_2 respectively, then the condition to keep the bridge in balance at any ambient temperature T_a would be as follows:

$$\frac{R_{W1}}{R_{W2}} = \frac{R_{W1} + R_{W1} \cdot \alpha \cdot (T_{W1} - T_a)}{R_{W2} + R_{W2} \cdot \alpha \cdot (T_{W2} - T_a)} = \text{const.}$$

where α is the temperature coefficient of resistivity which is considered equal and constant for both hot wires. This means that this condition is fulfilled at any ambient temperature T_a as long as the conditions at the two hot wires are identical.

METHODS OF OBTAINING MORE ACCURATE PRESSURE MEASUREMENTS BY COMPENSATING FOR TEMPERATURE DRIFT

In order to show that the aforementioned (p.5) temperature drift of single hot wires can be compensated to some extent by a second hot wire, the pressure hole on one side of the wedge was closed off tightly so that only the pressure on the other side was measured - in the same way as static pressures were measured (see p.5). In this case no further drifting of the reading was observed* because the second closed off hot wire within the wedge was in the same temperature environment and had the same temperature coefficient of resistivity as the first one.

However, any attempt to measure absolute pressure in this way would necessarily be limited in accuracy as through the effect of a changing ambient temperature T_a a particular reading loses its uniqueness. This means that the same reading may be produced by different combinations of T_a and p .

Fortunately there exist several methods to overcome this particular difficulty. Obviously the most straightforward one would be to make two electrical measurements. The first one would be just a determination of the pressure as described in this report. From calibration measurements, one gets in this way a series of calibration curves for different values of T_a . It is estimated that this method may yield an accuracy of about 1% or better for determining absolute pressures. There will probably always be some small discrepancy in determining the exact resistance of a hot wire, because of uncontrollable factors such as humidity, microscopic dust particles on the hot wire, etc. For most practical cases, however, this accuracy should be sufficient.

This method of making two electrical measurements, could be accomplished in essentially two different ways.

* This is true only as long as the working temperature of the wire is kept sufficiently close to its ambient temperature and as long as the temperature coefficient does not change abruptly with temperature. These conditions were well satisfied in our experiments.

a) One determines the resistance of a single hot wire for the temperature T_a (with very low current) and for T_w quickly, one after another, so that T_a cannot change appreciably in the meantime. Only one electrical lead per gage would be required here.

b) One can use a separate resistor (e.g. the Pt film resistor mentioned in the following paragraph) in the same environment as the hot wire to measure T_a . This enables one to make the two electrical measurements at exactly the same time, independently. Here two electrical leads per gage would be required.

Of course in all cases calibration measurements have to be performed prior to the actual use of the hot wire pressure gages in order to establish individual calibration charts for each hot wire.

Another completely different approach to eliminate any ambiguity from the readings is described by T. L. Smith in the appendix. This method would have the distinct advantage that only a single electric measurement is necessary for obtaining a unique pressure value and that only one electric lead per gage is required.

In the case of using either method, however, it would certainly be very inconvenient to provide for each hot wire pressure gage a second compensating wire of the same form separately, as was done in the experiment with the wedge described previously. Therefore, it is suggested that the compensating resistor be attached permanently to the ceramic tube (Fig. 1) itself by depositing on it a thin film of platinum in the way as shown in Fig. 6. Such metal film resistors are manufactured commercially* today at low cost and to very close tolerances with respect to resistance and temperature coefficient of resistance. The electrical connections could be made by silver conducting paint. As the common side of the hot wire and the film resistor could be grounded, only two leads per pressure gage would have to be brought out. It is, of course, possible to connect the gages to all kinds of self-balancing devices so that the readout could be made completely automatic. The

* e.g. by Film Ohm Corp. of New York City

nonlinear response of the hot wire is such that the sensitivity increases with decreasing pressure; this means that the gage is usable over a very wide range of pressures with a fairly good accuracy.

CONCLUSIONS

It has been shown in this paper that the hot wire pressure gages show promising possibilities for various applications in wind tunnel work. Their main advantages are very small size and weight, extremely high sensitivity at low pressures, and very short response time that should make them suitable even for use in shock tube wind tunnels and for research on turbulent pressure fluctuations. Their main shortcomings are highly nonlinear response that will probably require repeated separate calibration of each individual gage, the necessity to provide a compensating resistor and or to make two electrical measurements for determining just one absolute pressure, and the relatively tricky assembly of the hot wires themselves. The latter could be overcome if a suitable mass production facility is set up so that these gages would be commercially available at low cost. It is thought that such gages (as shown in Fig. 6), if installed in wind tunnel models, would be discarded with the models after finishing the tests. If one is interested merely in exploratory measurements the limited accuracy of the gages is not so important and it is probably in this case where they may find the wider application.

HERBERT J. BOMELBURG

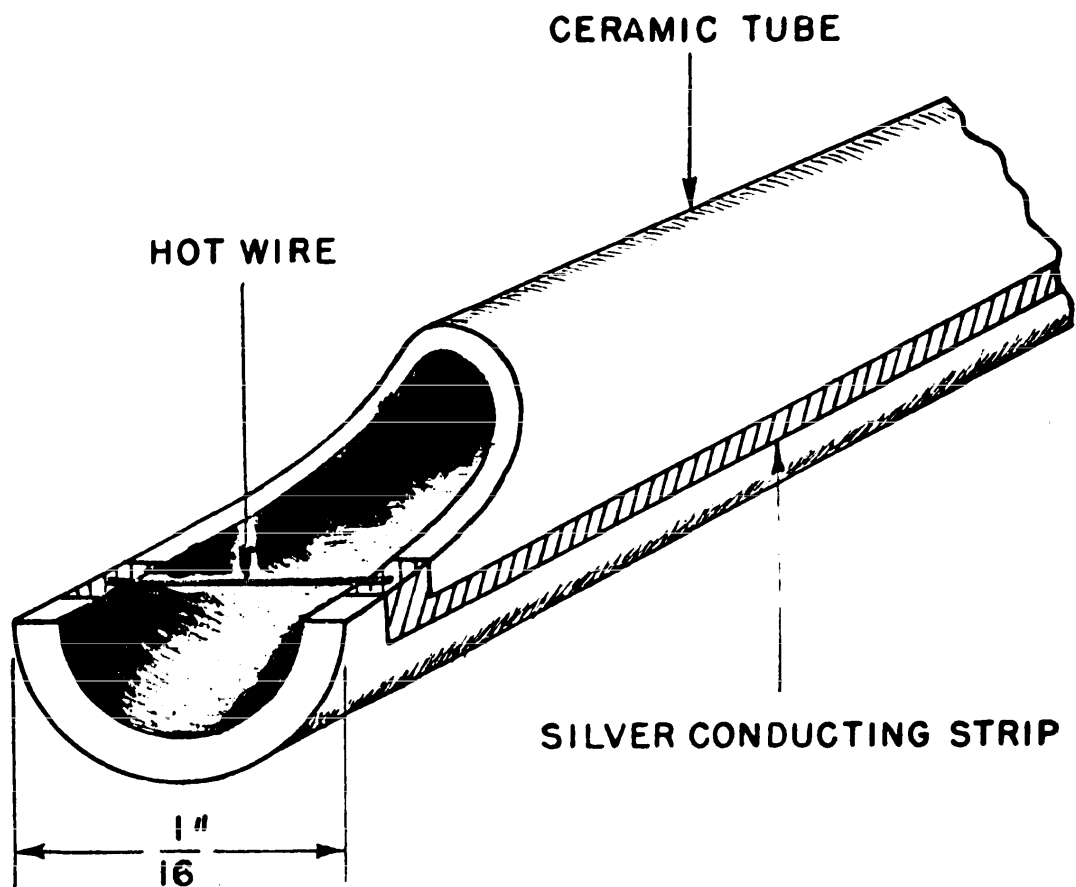


FIG. 1

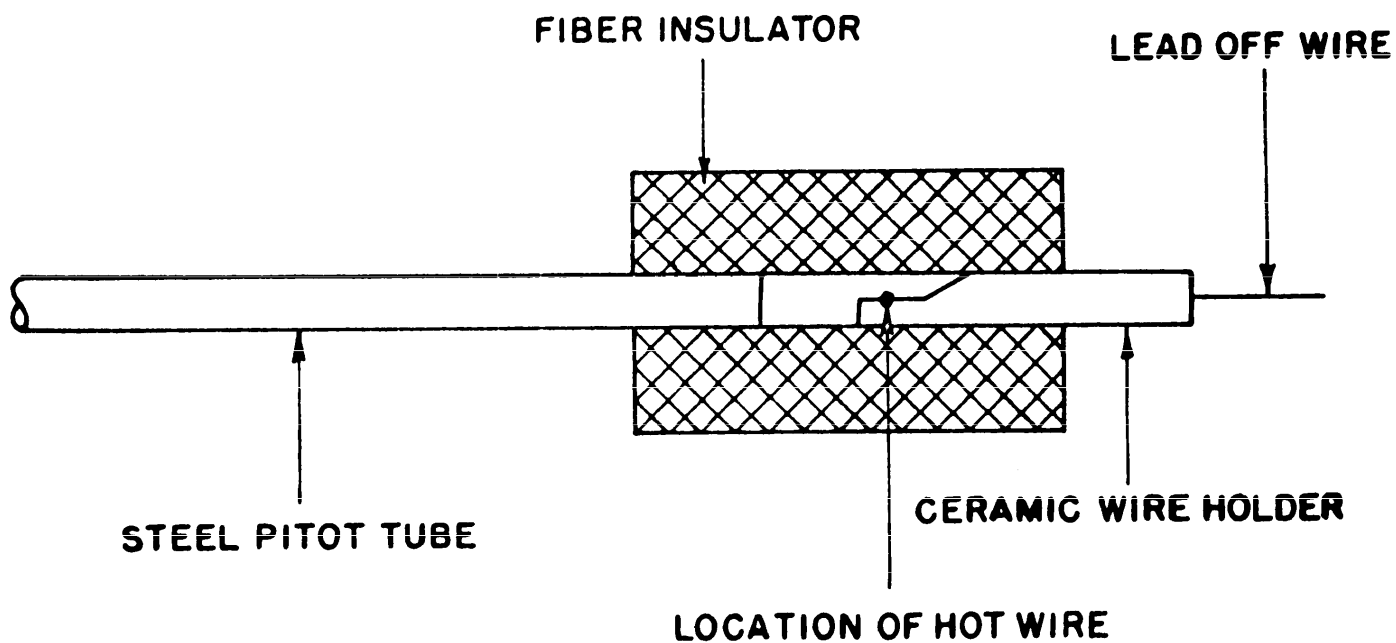


FIG. 2

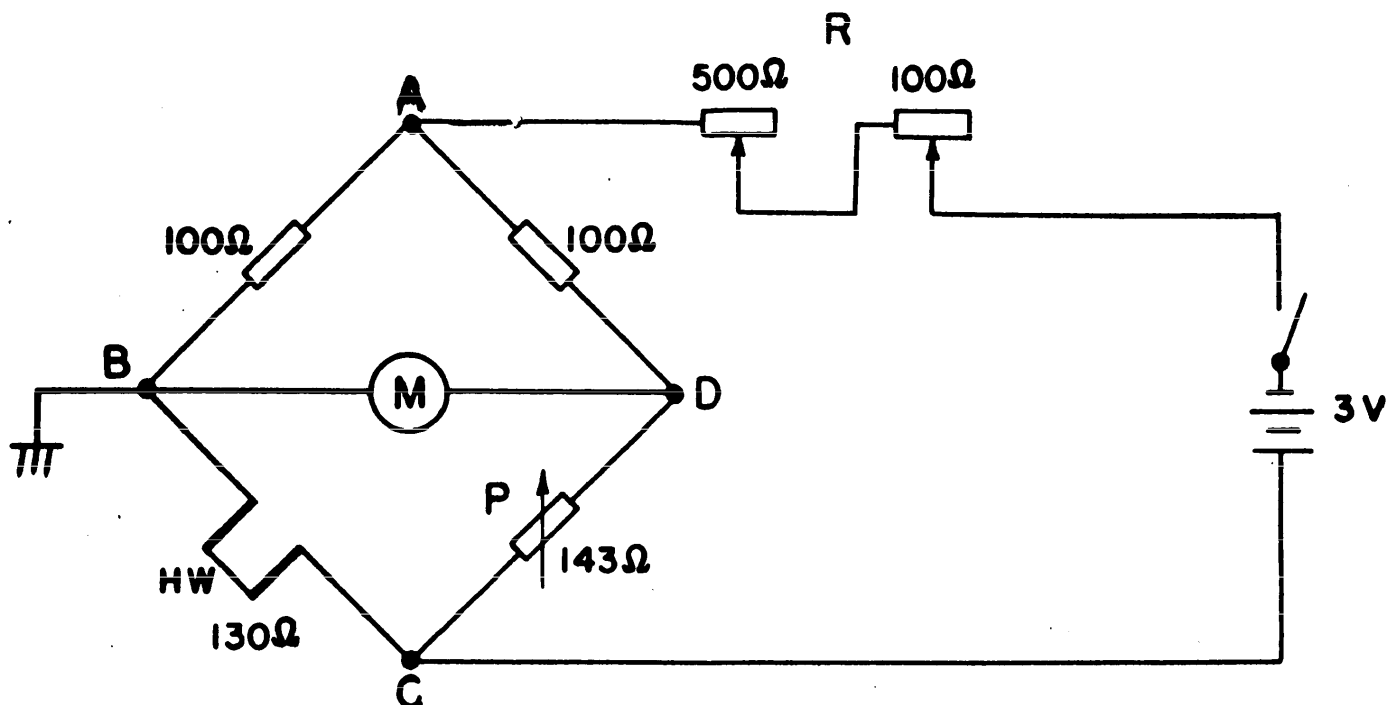


FIG. 3

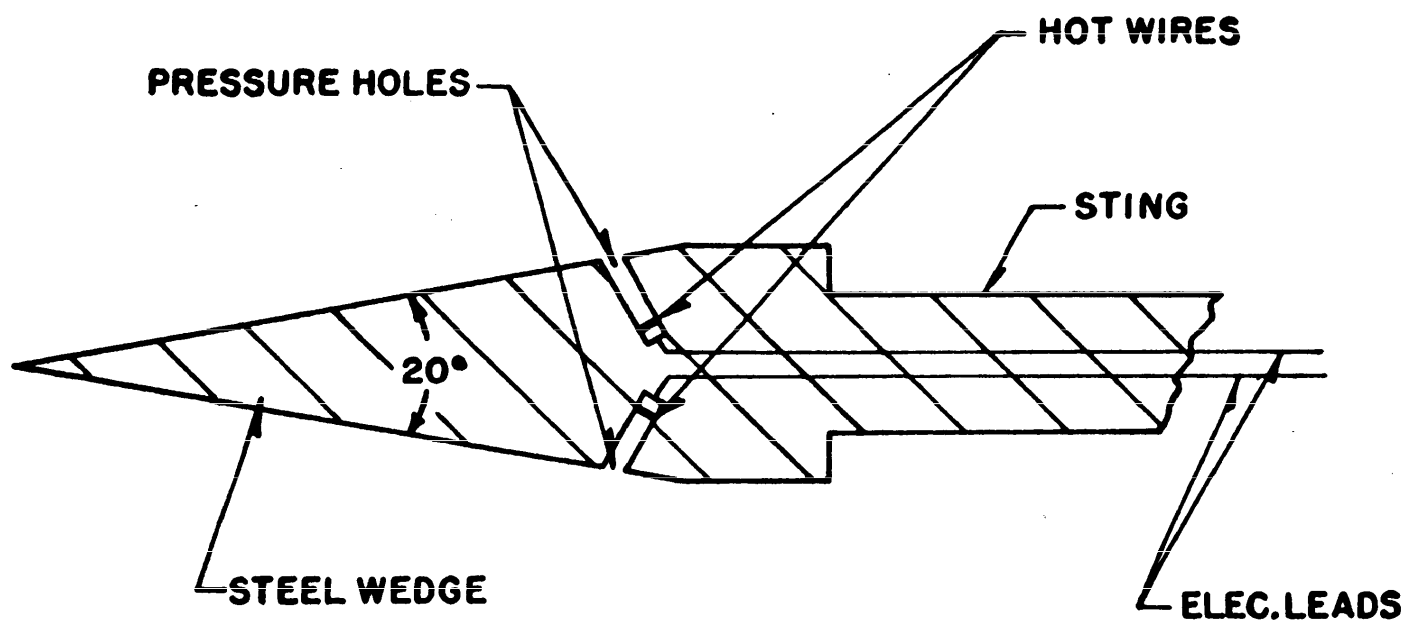


FIG. 4

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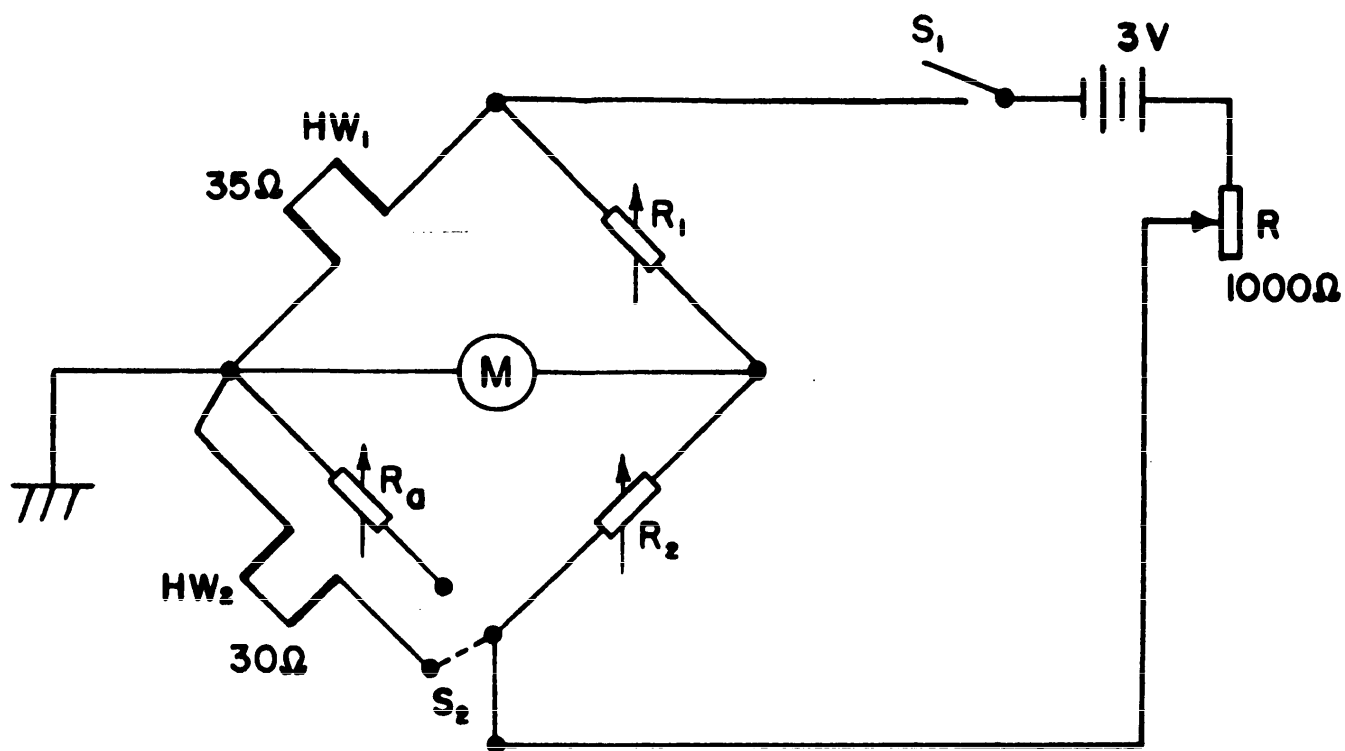


FIG. 5

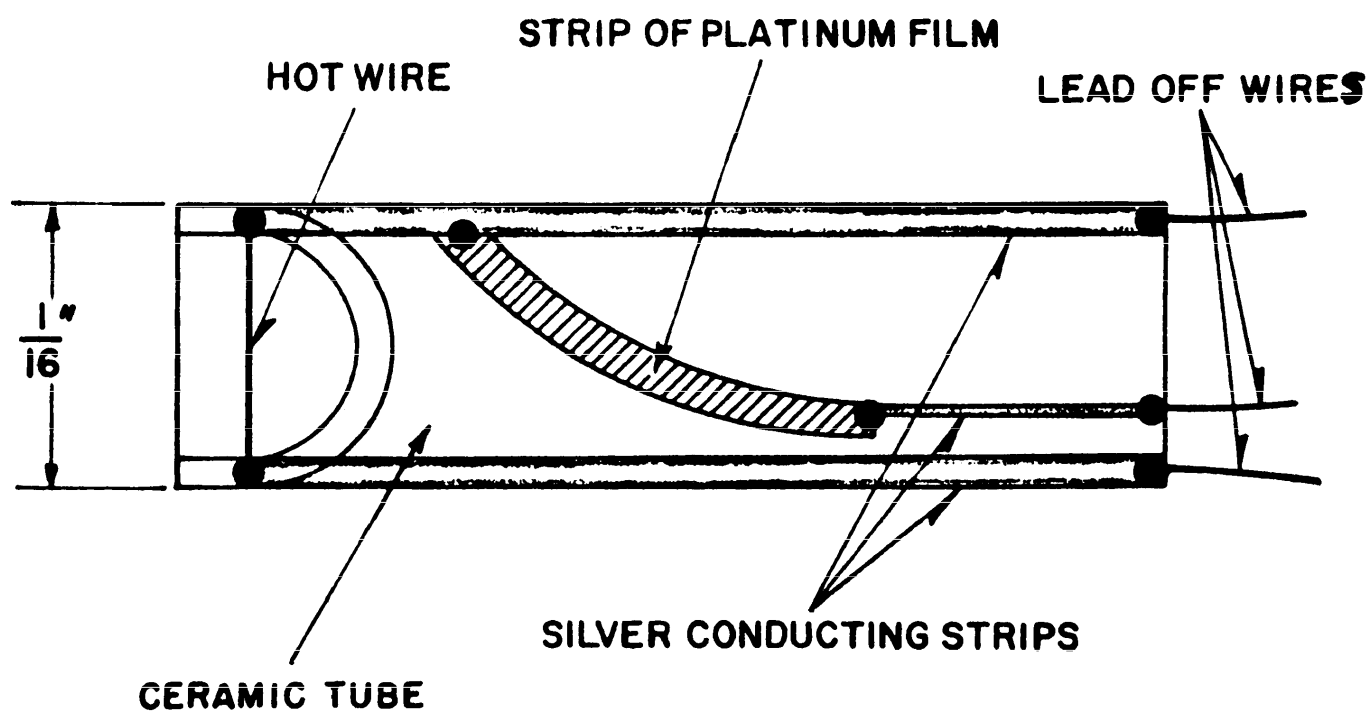


FIG. 6

APPENDIX

COMMENTS ON "MINIATURE HOT WIRE PRESSURE GAGES FOR WIND TUNNEL WORK" BY T. L. SMITH

My comment is related to the idea of using a compensating resistor which is not a hot wire; Dr. Bomelburg mentions this on page 12, but does not write equations for it. This compensating resistor turns out to need a different thermal coefficient of resistance than the hot wire; but if this is properly chosen and this compensating resistor has the same ambient temperature as the hot wire, the pressure can be found with one measurement, correctly compensated for variable ambient temperature to the first order.

Notation

- R_2 = resistance of the hot wire at some standard room temperature T_o
- R_1 = resistance of the compensating resistor at T_o
- α_W = temperature coefficient of resistance of the hot wire
- α_c = temperature coefficient of resistance of the compensating resistor

The compensating resistor is assumed to stay at the temperature T_a which is also the ambient temperature in which the hot wire is operating.

i = current which goes through the hot wire and compensating resistor in series, as one side of the bridge.

$$(1) R_W = R_2 (1 + \alpha_W(T_W - T_o))$$

$$(2) R_c = R_1 (1 + \alpha_c(T_a - T_o))$$

$$(3) i^2 R_W = C (T_W - T_a) \quad \text{Hot wire equation.}$$

I have assumed here that in the hot wire the heat loss follows the "Newtonian law", being proportional to the first power of its temperature rise above ambient; i.e., assume C in equation (3) is a function of p but

not of T_a . This Dr. Bomelburg also assumes, and I believe it is justified for small changes in T_a which would normally occur.

$$(4) \quad \frac{R_W}{R_C} = \frac{R_2}{R_1} \cdot \frac{1 + \alpha_W (T_W - T_a) + \alpha_W (T_a - T_o)}{1 + \alpha_c (T_a - T_o)}$$

We will assume that all $\alpha \Delta T$ terms are < 1 , so that equation (4) can be written

$$(5) \quad \frac{R_W}{R_C} = \frac{R_2}{R_1} \left[1 + \alpha_W (T_W - T_a) + (\alpha_W - \alpha_c)(T_a - T_o) \right]$$

From equations (3) and (1) combined

$$i^2 R_2 + i^2 R_2 \alpha_W (T_W - T_o) = C(T_W - T_a)$$

$$i^2 R_2 + i^2 R_2 \alpha_W (T_W - T_a + T_a - T_o) = C(T_W - T_a)$$

$$i^2 R_2 + i^2 R_2 \alpha_W (T_a - T_o) = (C - i^2 R_2 \alpha_W) (T_W - T_a)$$

$$(T_W - T_a) = \frac{1 + \alpha_W (T_a - T_o)}{\frac{C}{i^2 R_2} - \alpha_W}$$

Substituting this in (5), we get

$$(6) \quad \frac{R_W}{R_C} = \frac{R_2}{R_1} \left[1 + \frac{\alpha_W}{\frac{C}{i^2 R_2} - \alpha_W} + \left\{ \frac{\alpha_W^2}{\frac{C}{i^2 R_2} - \alpha_W} + \alpha_W - \alpha_c \right\} (T_a - T_o) \right]$$

We now note that the requirement that the bridge stay balanced or that the ratio (6) be independent of both pressure and ambient temperature is met if C/i^2 is a definite constant and if α_c is chosen so that the coefficient of $(T_a - T_o)$ in (6) is zero.

This gives the two equations

$$(7) \quad \frac{R_W}{R_C} = \frac{R_2}{R_1} \left[1 + \frac{\alpha_W}{\frac{C}{i^2 R_2} - \alpha_W} \right]$$

$$(8) \quad \alpha_C = \alpha_W \left[1 + \frac{\alpha_W}{\frac{C}{i^2 R_2} - \alpha_W} \right] \quad \text{coef. of } (T_a - T_o) \text{ 0 in (6)}$$

with the condition $C/i^2 R_2 = \text{constant}$, or

$$(9) \quad i^2 = k C(p)$$

We note that if we set the resistance R_3, R_4 of the other two legs of the bridge to require a 10% increase in resistance of the hot wire for balance, or in other words require that

$$\frac{R_W}{R_C} = 1.1 \frac{R_2}{R_1} = \frac{R_3}{R_4},$$

then we need $\alpha_C = 1.1 \alpha_W$ for the thermal coefficient of the compensating resistor, since the brackets are the same in equations (7) and (8).

We further need to note that i is the current in the variable side of the bridge only, and while i is proportional to $\sqrt{C(p)}$ and independent of T_a , the bridge resistance is not independent of T_a . Hence a correction for T_a has to be made, if bridge current is measured. This correction can be made very small, if the fixed resistance side of the bridge is made very high, so that the current through the hot wire is almost entirely the bridge current. There are disadvantages to doing this, as the bridge impedance as seen by the balancing galvanometer is high; this makes it more difficult to detect small unbalances, and increases the chance of error due to stray signal pick-up in the galvanometer.

If (7), (8) and (9) are satisfied, it will be seen that R_W is proportional to R_c , and so the variable side of the bridge has a resistance $R_W + R_c$ which is proportional to $1 + \alpha_c(T_a - T_0)$. If the other side of the bridge, resistors R_3 and R_4 , are also kept at the same temperature T_a and have the same temperature coefficient α_c , then the division of current between the two sides of the bridge will be independent of temperature, and the entire bridge current will be proportional to $\sqrt{C(p)}$ but independent of T_a .

T. L. SMITH

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